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Research of the Weldability of Iron Alloys

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
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Prepared by:

Clarence E. Jackson, Assistant Metallurgist

E. A. Rominski, Contract Employee

Reviewed by:

R. H. Canfield, Sr. Physicist, Superintendent, Division of Physical Metallurgy

Approved by:

H. M. Cooley, Captain, USN, Director

Distribution:
BuEng. (5)

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TABLE OF CONTENTS

APPENDICES

ABSTRACT

The determination of the effect of welding upon the properties of the parent metal is the aim of this study. Previous work carried out by another investigator from July, 1935, through January, 1938, is summarized in Navy report No. M-1419. In that work, the problem was attacked from the angle of preparing a small test specimen of the one-half width Charpy notched-bar type, reproducing the area immediately adjacent to a bead weld, this area of maximum hardness and largest grain size being considered the key to "weldability." The present investigators cannot concur in this observation. No tests were carried out showing that the overheated area when backed up by material with a milder heat treatment, such as occurs in a weld joint, would have the properties of the overheated area itself. Furthermore, recent investigations have shown that the geometry of the one-half width Charpy notched-bar is wrong and that at least a full width Charpy specimen is required for reliable correlation. Also, it has not been convenient in laboratory procedure to duplicate, in other than a very small test specimen, the thermal cycle which results in welding procedures.

In view of these and other considerations, the present investigators have prepared and tested specimens that have been subjected to the actual cycle of heat treatment obtained during welding. Initial tests of the relative toughness of the area adjacent to a weld in several hot rolled steels in the as rolled condition are herewith reported. The effects of normalizing, preheating, or stress relief annealing are not included in this report. A standard notched-bar test specimen of the full width and double width V-notch Charpy type, with the apex of the notch tangent to the fusion line has shown excellent promise in determination of notch toughness of the heat-affected zone in arc welding. Full automatic welding equipment has been designed and built which insures constant welding conditions.

Thermal studies have been carried out in order to better understand the thermal conditions and their effect on the parent metal adjacent to the deposited metal. Attention is called to Plate 1 in which is presented a summary of the effect of the thermal cycle of arc welding on the structure and hardness of the parent metal in the case of a plain carbon steel.

INTRODUCTION

(a) Authorization

1. This problem was authorized by Bureau of Engineering letter JJ46-1/L5(4-2-Ds) of 4 April 1935.

2. A summary report on the progress of the investigation was submitted under Naval Research Laboratory Report No. M-1419 of January 1938.

(b) Statement of Problem

3. The term "weldability", as applied to a steel, has not received any uniform definition by the welding industry, each investigator setting up his own definition for the term. In the last analysis, regardless of the type of laboratory or other tests used for qualification, the term "weldability" of a steel refers to the degree of ease of producing a weld joint satisfactory for the purpose intended. Any laboratory test must recognize this fact. Much of the confusion may be accounted for by the fact that in design for welding, each joint is a problem in itself and that all the variables of which there may be a dozen or more, such as thickness of plate, speed of travel, rate of power input, etc. will have their effect.

4. The present investigation considers in its first aspect a study of the toughness as measured by standard and double width Charpy notched-bar test specimens of the parent metal and heat-affected zone adjacent to a bead or single bevel groove weld.

5. The effect of normalizing, preheating, or stress relief annealing is not included in this report.

6. Thermal studies have been considered essential in order to better understand the thermal conditions and their effect on the parent metal adjacent to weld metal.

(c) Known Facts Bearing on the Problem (Theoretical Considerations)

7. Hardenability can only be considered as a rough criterion of a steel's "weldability", since steels of different compositions may for an equivalent hardness possess different degrees of toughness or brittleness.

8. The history of notched-bar testing shows that considerable attention has been paid to the design of the test bar. Experiments on the width of the test piece have shown that narrow bars were not capable of making the proper distinction between materials of different toughness because the restriction at the notch was not sufficient to produce the necessary notch effect. On this account, a 10 mm (.394") square bar has predominated in notched-bar testing.

9. The general effect of change in width of the notched-bar is shown by Plate 2. The actual values given will, of course, change with variations in the composition of the steel under test. The greater the notch sensitiveness of a particular steel the greater spread will be shown in this type of curve.

10. The effect of heat treatment on the Charpy notched-bar value is shown by Plate 3. Here again the actual values and the exact position of the curves will be determined by the particular steel under investigation and the particular heat treatment to which the specimen has been subjected.

11. A search of the literature disclosed many investigations upon the metallurgical behavior of the heat-affected zone adjacent to a weld joint or bead. Several investigators have measured thermal conditions adjacent to a weld. However, no publication correlates the actual metallurgical changes, as predicted by the Fe-C equilibrium diagram, with the time-temperature cycle in welding processes.

MATERIAL UNDER TEST

12. The series of laboratory and commercial steels which were usedd in the previous studies of this problem has supplied the material for this investigation. The analyses of the plate material appear in Table 1.

13. No. 78 Airco, Grade EA, Class 2, heavy coated electrodes, 3/16-inch in diameter, were used as the standard in this welding study.

14. Several other makes of electrodes were also available for thermal studies. Among these are included:

Una 3200 - 3/16 inch diameter
Murex Cresta - 3/16 inch diameter

METHODS OF TEST

15. It is felt that a full automatic control of welding conditions is a fundamental requisite in making test welds. While it is true that much perfect weld metal is deposited manually by skilled welders, it is equally true that test work requires the maintenance of uniform values of current, arc voltage, and speed of travel of electrode. As a result, after considerable experimental and design work, a full automatic welding control has been built which closely maintains the welding conditions to a predetermined value. This insures comparable and reproducible results.

16. Thermal conditions have been established showing the cycle of temperature through which the metal adjacent to the deposited metal passes. In the determination of this time-temperature relation,

Pt, Pt-10% Rh thermocouples made from No. 40 B&S gauge wire were mounted in a 2 mm (.079") thermocouple tubing and inserted into holes drilled in the bottom face of the test plate, the thermocouples being located at various distances from the deposited metal. This is clearly shown in Plate 4. Care was taken to insure good contact of the thermocouple bead with the test plate. A movie camera was used for each thermocouple to record simultaneously the transient readings of a millivolt meter and a stop-watch as the bead weld was made on the top face of the test plate. Type of electrode and power input has been varied in tests so far.

17. Temperature measurements have been made on the weld metal, during deposition, using an optical pyrometer. An operator trained in the checking of the temperature of many steel casting heats was available and consistent results were obtained.

18. Single bead welds were deposited transverse to the direction of rolling on 6 x 7 x 1/2" plates in the as rolled condition. The electrode was used with reverse polarity at 175 amperes, 25 volts, and a speed of travel of 6 inches per minute. An approach plate was used in order to make a greater portion of the test plate available for investigation. The plates were sectioned to give specimens for micro and macro examination. Five standard (.394" x .394" x 2.165") and two double width (.394" x .788" x 2.165") notched-bar bead weld specimens were also prepared. After these were ground and etched the location of the V-notch was determined by using a comparator or micrometer for measurement. The apex of the standard V-notch was machined tangent to the fusion line as in Plate 5. Five standard and two double width specimens were also made for each plate material tested.

19. In a second series of test plates, single bevel groove welds were prepared, one plate being scarfed to a 45° angle, and the other being cut with no scarf. A backing strip was used with a root opening of slightly over 3/16 inch. The weld was completed with six passes using reversed polarity, at 190 amperes, 27 volts, and a travel of 5" per minute. During the first two beads, the plates required positioning in order to obtain full penetration at the root of the weld groove. Six standard width, notched-bar specimens were machined, three with the V-notch at the fusion line and three with the V-notch at the outer edge of the heat-affected zone as shown in Plate 6. It is felt that weld joint, double width specimens would add much to the weld joint data.

20. Vickers Brinnell hardness measurements have been made on the bead weld macro specimens using a 10 Kg load with the diamond pyramid. Macro- and micro-photographs are being made and will be included in a future report. The notched-bar specimens were broken in an Amsler pendulum type machine at temperatures between 70 and 75°F.

DATA OBTAINED

21. Time temperature cycles in bead welds are presented in Plates 7 to 14, current and type of electrode being varied as indicated. The relation of power input to plate material melted is presented in Plate 15.

22. The relation of thermal conditions, structure, and hardness as the result of arc welding a mild carbon steel is presented in Plate 1.

23. Notched-bar test values for the plate material, bead weld and weld joint specimens together with a hardness summary for the bead weld are presented in Table 1. For convenience in comparison, the half-width keyhole and weld quench test values previously presented are re-tabulated.

CONCLUSIONS AND RECOMMENDATIONS

(a) Facts Established

24. Certain thermal distribution curves showing the time-temperature cycle in bead welds have been established.

25. The use of standard width, 10 mm (.394") and double width, 20 mm (.788") Charpy notched-bar test specimens definitely gives information regarding toughness of plate material in the as rolled and welded condition. This information is not given by one-half width, 5 mm (.197") Charpy notched-bar test specimens.

(b) Collateral Facts with Recommended Application

26. Using 3/16" commercial electrodes, No. 78 Airco, Murex Cresta, and Una 3200, under identical conditions, no difference could be noted in the thermal cycle through which a plain carbon steel plate passed during welding.

27. The time-temperature thermal distribution in a bead weld indicates that the time of cooling of one-half inch thick test plates increases with the power input.

28. The volume of parent metal melted decreases with a decrease in power input.

29. These two facts have direct and opposite effects in the practical welding of low alloy steels. In steels which alloy soundly with the electrode deposit, an increase of power input will reduce the danger of the drastic weld quench. On the other hand, if the quality of the weld metal deposited suffers due to parent metal dilution, the power input must be kept at a minimum.

30. Microstructure, thermal conditions and hardness values for a mild steel can be correlated with changes predicted by the iron-carbon equilibrium diagram. Since the heat-affected zone in a bead weld contains the whole gamut of heat treated steel, studies of thermal conditions and microstructures may be used in predicting certain portions of equilibrium diagrams. The effects of low alloy additions in shifting known equilibrium phases may also be studied. Fundamental data of this type would help much in a clearer understanding of the metallurgy that takes place in the parent metal adjacent to a weld zone.

31. Plate 4, a longitudinal cross-section of a bead weld, shows the location of a set of five thermocouples used for measuring the thermal cycle at various distances from a bead weld. It is interesting to note the roll of the metal as it has been deposited. It was necessary to section the plate along the line of thermocouples in order to determine their distances from the weld metal. The curve to the right in Figure 2 shows the relation of maximum temperature and distance from weld metal for a low carbon steel. The curve is not continuous, a change in slope taking place between 774° C. and 910° C., indicating the A_3 transformation.

32. Across the heat-affected zone of the bead weld, as seen in Plate 1, exists the whole range of heat-treated material. Any welding procedure will necessarily produce conditions comparable to both good and bad heat treating practice. At the weld-metal parent-metal interface, the material has been heated up to the melting point of the parent metal and cooled rapidly or quenched through the austenitic range by the surrounding parent metal. The grain growth in this zone will depend directly upon the maximum temperature attained over the A_3 point. The final structure will be dependent upon the composition of the steel and the rate of cooling. ?

33. The very coarse structure just below the weld-metal, parent-metal interface is a condition typical of over-heated steel. The degree of grain growth is greatest just below the fusion line and becomes less as the maximum temperature decreases until the A_3 transformation point is reached. The normal result of heat-treatment as ordinarily practiced is a refined grain size, and the grain growth associated with welding is the result of the steel having been at temperatures well in excess of the A_3 transfomation point. In general, the higher the hardening temperature, the slower is the critical rate of cooling necessary to develop full hardness.

34. In the area which has reached a maximum temperature below the A_3 and above the A_1, austenite begins to form which in turn is transformed to the ferrite-cementite phase during the cooling cycle.

35. For temperatures just below the A_1 transformation, the carbide particles tend to diffuse and coalesce into spheroidal particles.

36. Transformations and changes require a definite amount of time but are hastened by increased temperatures. Lower carbon and alloy contents will tend to permit the changes to take place at shorter intervals of time. The effect of higher carbon and alloy contents is to increase the sluggishness of transformations and to shift the critical rate of cooling to a higher value.

37. It is to be emphasized that in the heat-affected zone of the parent-metal, adjacent to a weld, the maximum temperature attained and the rate of cooling at any point will determine the final structure produced. As we leave the fusion line, the temperature difference between any point and the parent-metal becomes less and less, which in turn will reduce the thermal gradients and decrease their metallurgical effects. The use of preheating and multiple bead deposits will affect the structure of the parent-metal only insofar as the thermal cycle through which a particular structure passes is affected.

38. A typical crack occurring adjacent to a bead weld is shown on Plate 16. It is to be noted that the shape of the bead weld on the steel plate is such as to produce stress concentration at the toe of the weld. The crack initiates in the parent metal at this point adjacent to the fusion line and progresses in the direction of least resistance through the heat-affected zone.

(c) Discussion of Data

39. As a general survey of the data presented in Table 1, Plate 17 has been plotted, comparing graphically the values of standard width V-notched with the half-width keyhole-notched specimens, At first glance, the correlation would seem to be poor but when one recognises the variables which affect the notched-bar test, such as shape of bar, size of bar, and type of notch, it is surprising that the correlation is as good as it is. It has been pointed out by Hoyt(1) and McAdam and Clyne(2) that a narrow notched test specimen may, at room temperature, have a higher notch toughness than a wider specimen. Notch sensitive material will show a decided decrease in energy absorption per unit area as the speci-

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(1) Hoyt, S.L., Notched Bar Testing. Metals and Alloys, Vol.7, 1936, pp. 5-7, 39-43, 102-106, and 140-142.

(2) McAdam, D.J.,Jr. and Clyne, R.W. The Theory of Impact Testing: Influence of Temperature, Velocity of Deformation, and Form and Size of Specimen on work of Deformation. American Society for Testing Materials, Proceedings, Vol. 38, 1938, Part II, Technical Papers, pp. 112-132.

mens increase in width. The curves presented in Plate 2 are typical curves of this phenomenon. For different steels, the set of curves may be shifted laterally to the right or to the left. The greater the width of a specimen, notched on only one side, the greater is the hindrance to contraction along the notch. Increase in specimen width in any particular steel, like an increase in depth or sharpness of the notch, raises the temperature at which the steep, low temperature drop of the curve occurs. Heat treatment will also shift the notched-bar values. Grain size and degree of uniformity of microstructure will also affect the notched-bar value. Typical effects of heat treatment are shown by the curves given in Plate 3, which represent data obtained on a carbon steel. Cognizance of these variables, the type of specimen and the heat treatment, is essential in interpreting notched-bar values. Notched-bar testing will only be of full value when the variables which affect its results are recognized.

40. Hardenability can only be considered as a rough indication of a steel's weldability, because ~~some~~ steels of different compositions may, for an equivalent hardness, possess different degrees of toughness or brittleness. However, this approximate criterion of hardness may be used and the steels divided into four groups. Group 1 would include steels in which the average hardness of the heat-affected zone of the parent metal is below 200, group 2 - 200 to 250, group 3 - 250 to 325, and group 4 - those showing hardnesses above 325. Group 1 includes steels which may be welded without preheating and without necessity of stress relief annealing after welding. Steels numbers 1, 2, 5, 6, and 9 are plain carbon steels, hardenability being kept at a low level by reason of the low carbon and manganese content. Notch sensitiveness shown by the high ratio of double width to single width test values in these steels is low both in the as rolled as well as the welded condition. Steel No. 20, in spite of low hardenability, shows a decrease in the double width Charpy notched-bar test value compared to the single width. This indicates that this steel is notch sensitive at room temperature and would make the use of this steel questionable. Welding heat-treatment does not change this behavior. Comparison of single and double width notched-bar specimens of plate material and of the bead weld type show some beneficial effect of the particular thermal cycle used in these welding tests. Weld joint properties show an improvement. This behavior of Steel No. 20 is not shown by the 1/2 width specimens. In Steel No. 29, it was not possible to obtain a break across the annealed zone in the weld joint specimen, as in each test an irregular break down through the fusion line occurred. From this series of tests, the samples of Steels Nos. 27 and 32 indicate the best welding properties. Tests on other samples, and a wider range of tests, will be required before further recommendations can be made.

41. Group 2 includes those steels which require slight preheating for heavier sections; and stress relief annealing is advisable for lighter sections and mandatory for heavier sections. Steel numbers 3, 10, 13 and 14 are plain carbon, steels with somewhat higher carbon and manganese than the steels of Group 1. Steel No. 13 with some degree of notch sensitivity at room temperature is not particularly affected by the present welding thermal cycle. Steel No. 18, a carbon-.50% molybdenum and Steel No. 23, a copper-molybdenum steel show good notched-bar properties in all cases. Steel No. 30, a Mn-Ni-Cu-Mo steel shows exceptional improvement in notched-bar values, in the heat-affected zone of the weld joint specimen and in the bead weld test. In consideration of the notched-bar test values, Steels Nos.10, 23 and 30 may well be included in Group 1.

42. Group 3 includes those steels which require preheating to 300° F. or higher and a stress relief anneal is necessary for both light and heavy sections. Steel No. 4 is a plain carbon steel which has a coarse grain, indicating a finishing temperature considerably above the A_3 transformation point. The coarse grain enhances the effect of carbon and manganese giving brittle notched-bar results in all cases. No double width test values were obtained. Steel No. 11 is a steel with carbon of 0.29%, and manganese of 1.06%. All notched-bar test values are comparatively high, although the ratio of the standard to double width notched-bar in the plate material is low. Weld heat treatment gives an improved ratio. The coarse grain structure has shifted the notched-bar temperature curve to a higher temperature level for the 1/2 width weld quench. Steel No. 19, containing 0.79 per cent molybdenum, shows some decrease in the ratio of the double to the standard width bead weld notched-bar, when compared with the ratio for plate material. This indicates an increase in notch sensitiveness of this material when subjected to weld heat treatment. The standard width weld joint annealed zone shows a decided improvement. Steel No. 22, a manganese-vanadium steel, is somewhat more notch sensitive in the bead weld test than as rolled. Steel No. 35, a carbon, manganese, 2.31 per cent nickel steel, is decidedly influenced in its notch sensitivity by the present welding thermal cycle. Steels Nos.19 and 22 may well be included in Group 2 classification.

43. Group 4 includes those steels whose average hardness of heat-affected zone would require preheating to 400° F or higher and the welded structure not being cooled until stress relieved or annealed. Steel No. 33, a 4 to 6 per cent chromium-molybdenum steel is decidedly sensitive to the present weld thermal cycle, as shown by effects of the bead weld test. The double width specimen of the plate material does not show as high a notched-bar value as the standard width, although both of these values are high. Steel No. 37 is decidedly influenced in its

notch sensitivity by the present welding thermal cycle. Steel No. 38, a chromium-molybdenum steel with high initial hardness and coarse grain in the as rolled condition, shows low notched-bar value which is decidedly improved by the bead weld heat treatment. Despite the high hardness, this steel is a better welding steel than Steel No. 3, for example, and may well be placed with the steels of Group 3 or even Group 2.

SUMMARY AND CONCLUSIONS

44. The use of a single and a double width Charpy V-notched test specimens of a welding steel in as rolled condition may be used to indicate the degree of notch sensitivity of a welding steel.

45. The use of a single and a double width Charpy V-notched test specimen of a welding steel with the apex of the notch tangent to the heat-affected zone under a bead weld may be used to indicate the degree of notch sensitivity of the welding steel after being subjected to a weld thermal cycle.

46. By comparing the notched-bar value of plate material with that of the bead weld notched-bar, an indication is obtained of the effect of weld heat treatment on the notch sensitivity.

47. The use of the 1/2 width Charpy notched-bar test presents results under only one condition and the data are in no way complete. Also, inherent in this size of specimen is a lowering of the temperature at which the steep low temperature drop of the total work curve occurs; hence, ductile breaks and erratic conclusions are possible.

48. The use of bead weld notched-bar specimens takes into consideration the effect of the annealed zone in those steels which have a brittle annealed zone as well as those steels which have a brittle fusion zone backed up by a less brittle annealed zone.

49. Welding technique may be varied in the preparation of the bead weld test specimen in order to determine the critical rate of cooling below which the thermal cycle may produce erratic behavior.

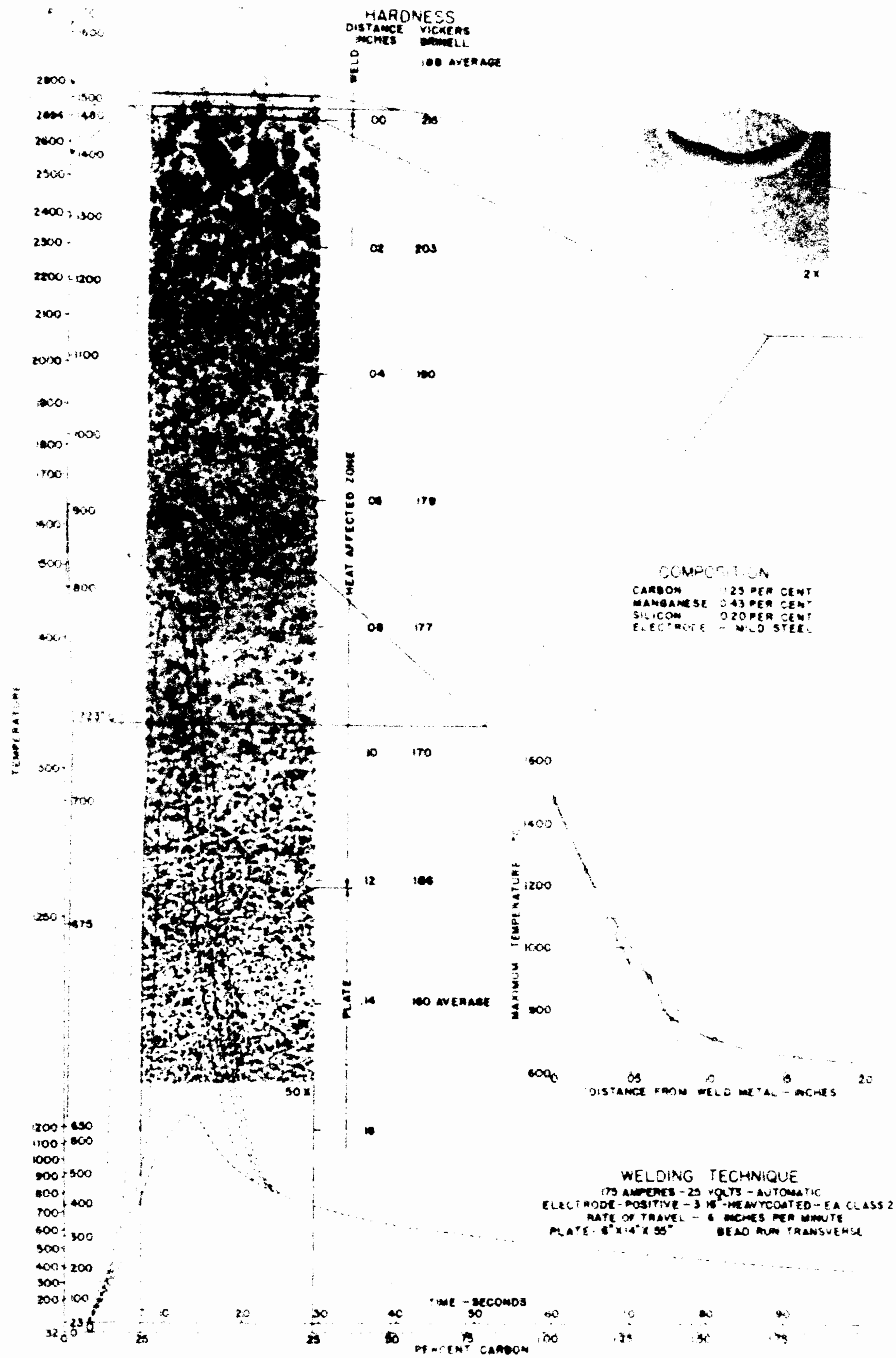
50. Welding technique and conditions, that is, preheat, post heat, plate thickness, and welding process, may be varied in preparation of the bead weld notched-bar to suit commercial practice used in any particular welding shop. Standard conditions should be set up for comparison purposes. Some steels will improve decidedly under special welding technique.

51. Data have been presented suggesting the use of single and double width V-notched-bar of the Charpy type in the study of notch toughness of plain carbon and low alloy steel plate material in the as rolled and welded condition.

TABLE I

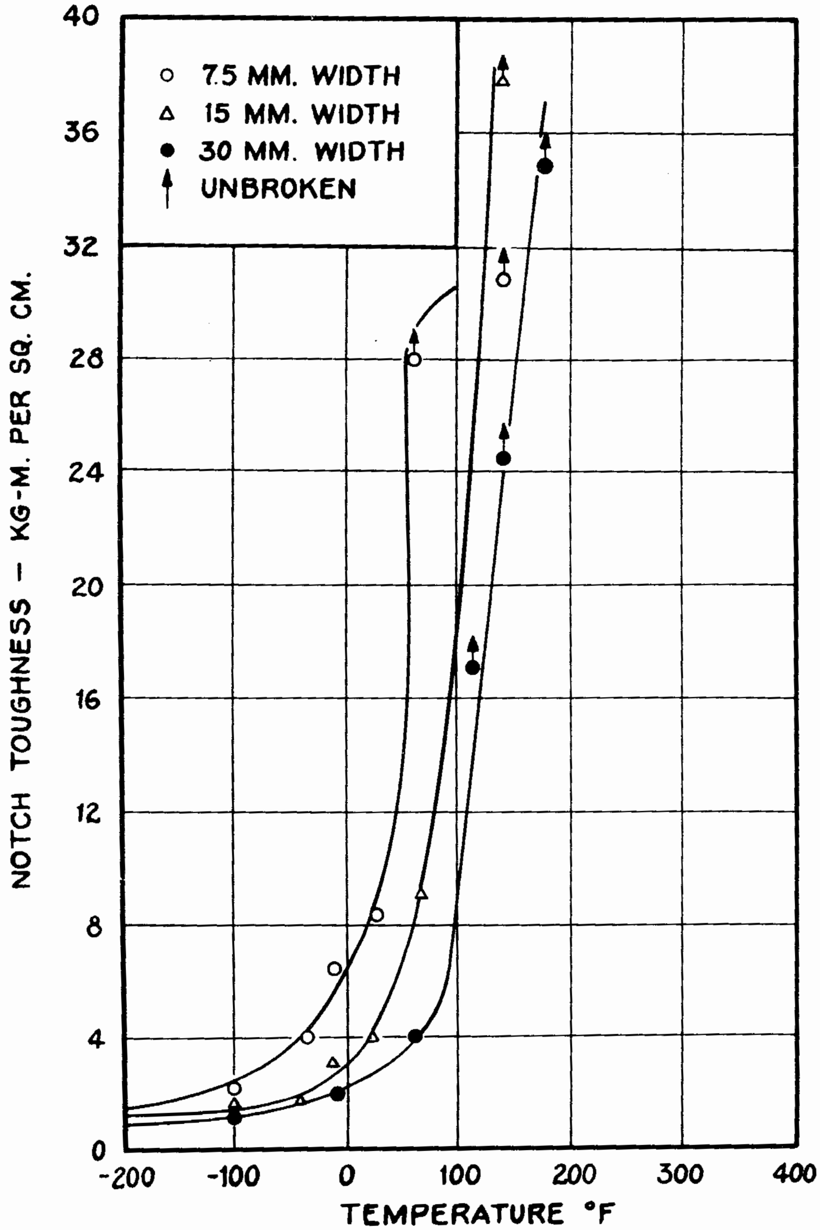
THE CHEMICAL ANALYSIS, NOTCHED BAR VALUES IN FOOT-POUNDS AND VICKERS BRINELL HARDNESS FOR STEELS INVESTIGATED

Steel No.	Chemical Composition - Per Cent C	Mn	Si	Ni	Cu	Mo	Cr	V	1/2 Width Charpy Keyhole Notched Bar Plate*	Weld Quench	Charpy V-Notched Bar Specimen for As Rolled Plate Material 1/2 Width (5 mm)	Standard (10 mm)	Double Width (20 mm)	Bead Weld Charpy V-Notched Bar Specimen Standard	Double Width	Weld Joint Charpy V-Notched Bar Specimen Standard Width Fusion Line	Annealed Zone	Hardness Vickers Brinell 10 KG Load Heat Affected Zone Plate	Max.	Average	Steel No.
1	0.17	0.41	0.17						16	18	32 (D)	55	101	44	85	39	55	162	215	176	1
2	0.25	0.43	0.20						16	15	26 (D)	40	63	38	70	37	36	168	227	196	2
3	0.35	0.68	0.23						19	13	18 (D)	17.2	29	17.1	26	47	18	194	246	226	3
4	0.44	0.65	0.24						10	2½	8.4	10	---	12	--	30	8	220	333	265	4
5	0.21	0.38	0.003						17	12½	25 (D)	25	46	38	80	34	25	156	215	180	5
6	0.27	0.47	0.002						16	15	26 (D)	26	48	39	50	57	40	168	233	192	6
9	0.24	0.48	0.23						9	9	18 (D)	41	73	35	60	34	34	156	206	184	9
10	0.27	0.74	0.21						19	9	31 (D)	49	94	38	74	42	44	174	237	205	10
11	0.29	1.06	0.25						22	7	46 (D)	107 (D)	147	76 (D)	139	49	127 (D)	192	369	258	11
13	0.26	0.46	0.005						14	16	24 (D)	30	36	32	40	45	37	166	282	222	13
14	0.28	0.54	0.058						13	12	19 (D)	22	40	27	46	38	24	164	237	206	14
18	0.22	0.47	0.18			0.50			24	25	38 (D)	82 (D)	115	76	103	45	49	180	240	227	18
19	0.20	0.50	0.17			0.79			25	20	39 (D)	55	91	57	75	54	95	190	270	252	19
20	0.24	0.46	0.001						16	15	26 (D)	39	35	48	44	41	54	160	209	189	20
22	0.18	1.40	0.21					0.12	13	7½	16 (D)	32	56	31	49	46	32	216	351	287	22



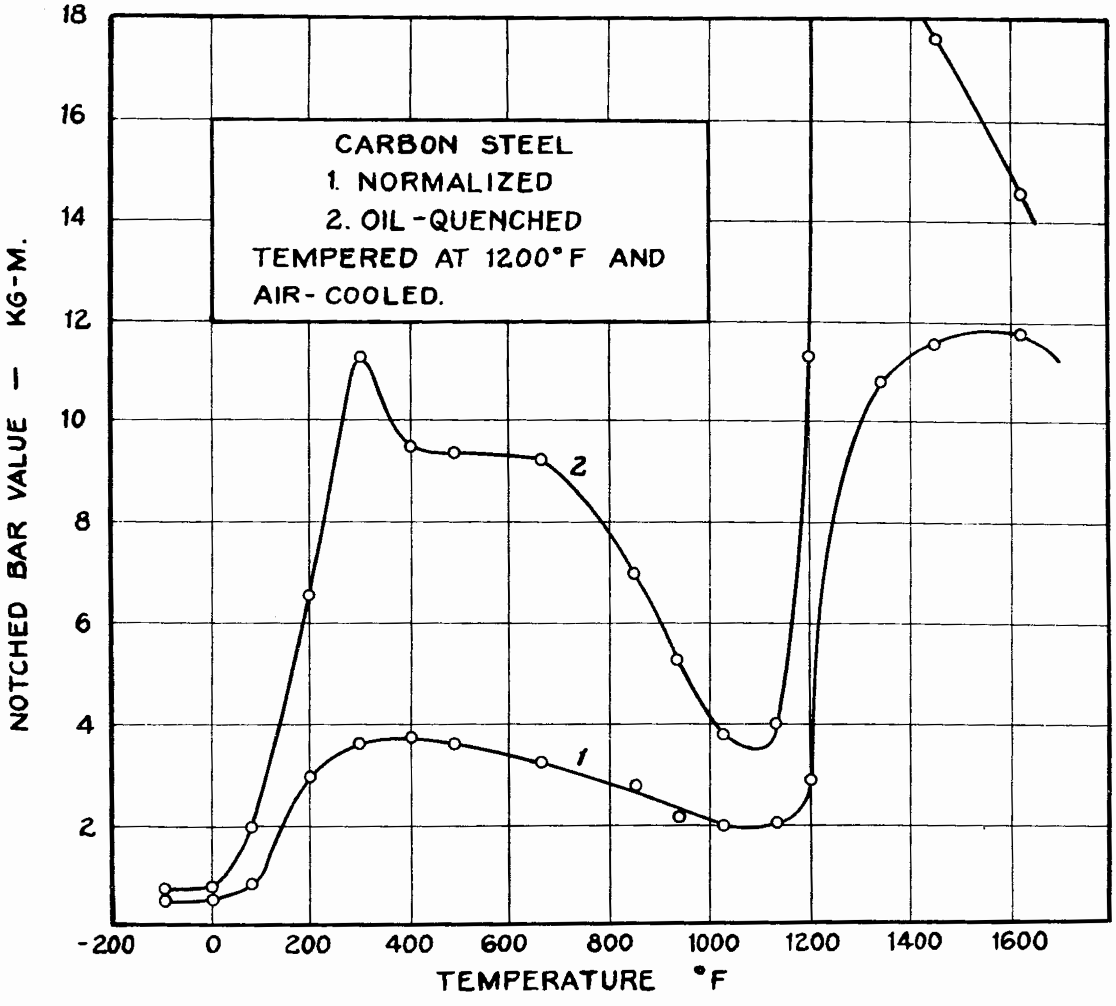
RELATION OF THERMAL CONDITIONS, STRUCTURE AND HARDNESS IN ARC WELDING MILD CARBON STEEL

PLATE I

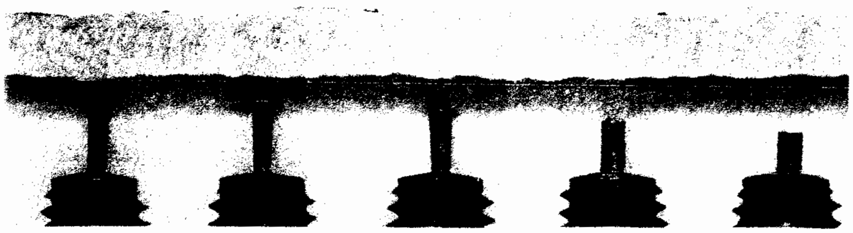


RELATION OF THE WIDTH OF A NOTCHED BAR TEST SPECIMEN ON THE TEMPERATURE OF COLD BRITTLENESS. (MAURER AND MAILÄNDER)

PLATE 2



EFFECT OF HEAT TREATMENT ON THE VARIATION OF NOTCHED BAR VALUE WITH TEMPERATURE. (GREAVES AND JONES)



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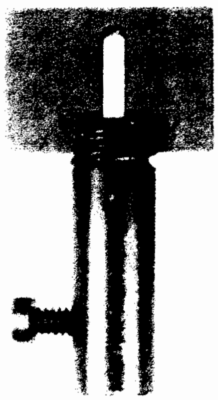


1.6 x

LOCATION OF THERMO-COUPLES WITH RESPECT TO A BEAD WELD AND ARRANGEMENT FOR CLAMPING THERMO-COUPLES IN PLACE.

2 ×

2 ×

2 ×

BEAD WELD NOTCHED-BAR SPECIMENS.

2×

2×

2×

WELD JOINT AND WELD JOINT NOTCHED-BAR SPECIMENS.

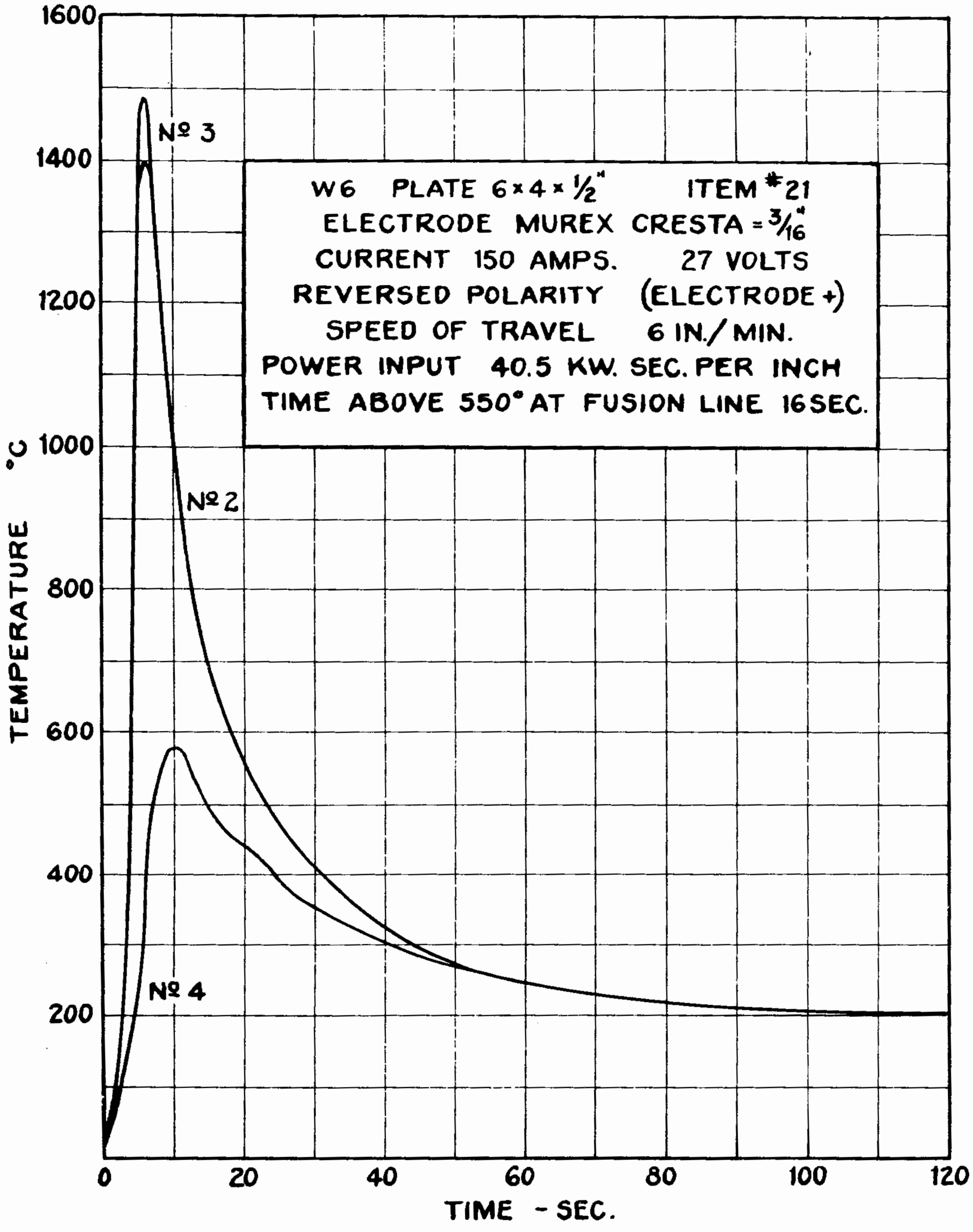

W6 PLATE 6×4×1/2" ITEM #21
ELECTRODE MUREX CRESTA = 3/16"
CURRENT 150 AMPS. 27 VOLTS
REVERSED POLARITY (ELECTRODE +)
SPEED OF TRAVEL 6 IN./MIN.
POWER INPUT 40.5 KW. SEC. PER INCH
TIME ABOVE 550° AT FUSION LINE 16 SEC.
Nº 3
Nº 2
Nº 4
TEMPERATURE °C
1600
1400
1200
1000
800
600
400
200
0
20
40
60
80
100
120
TIME - SEC.

PLATE 7

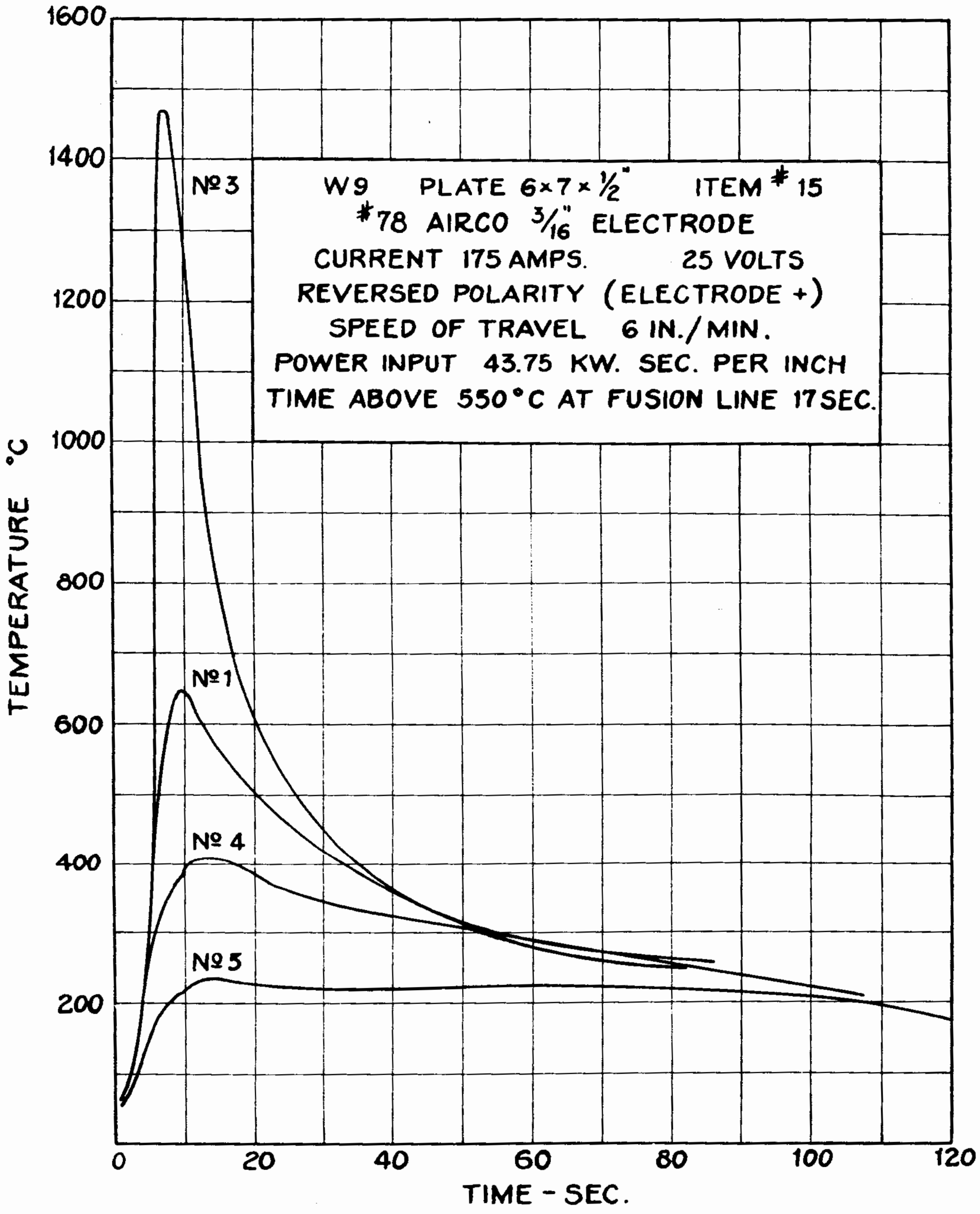
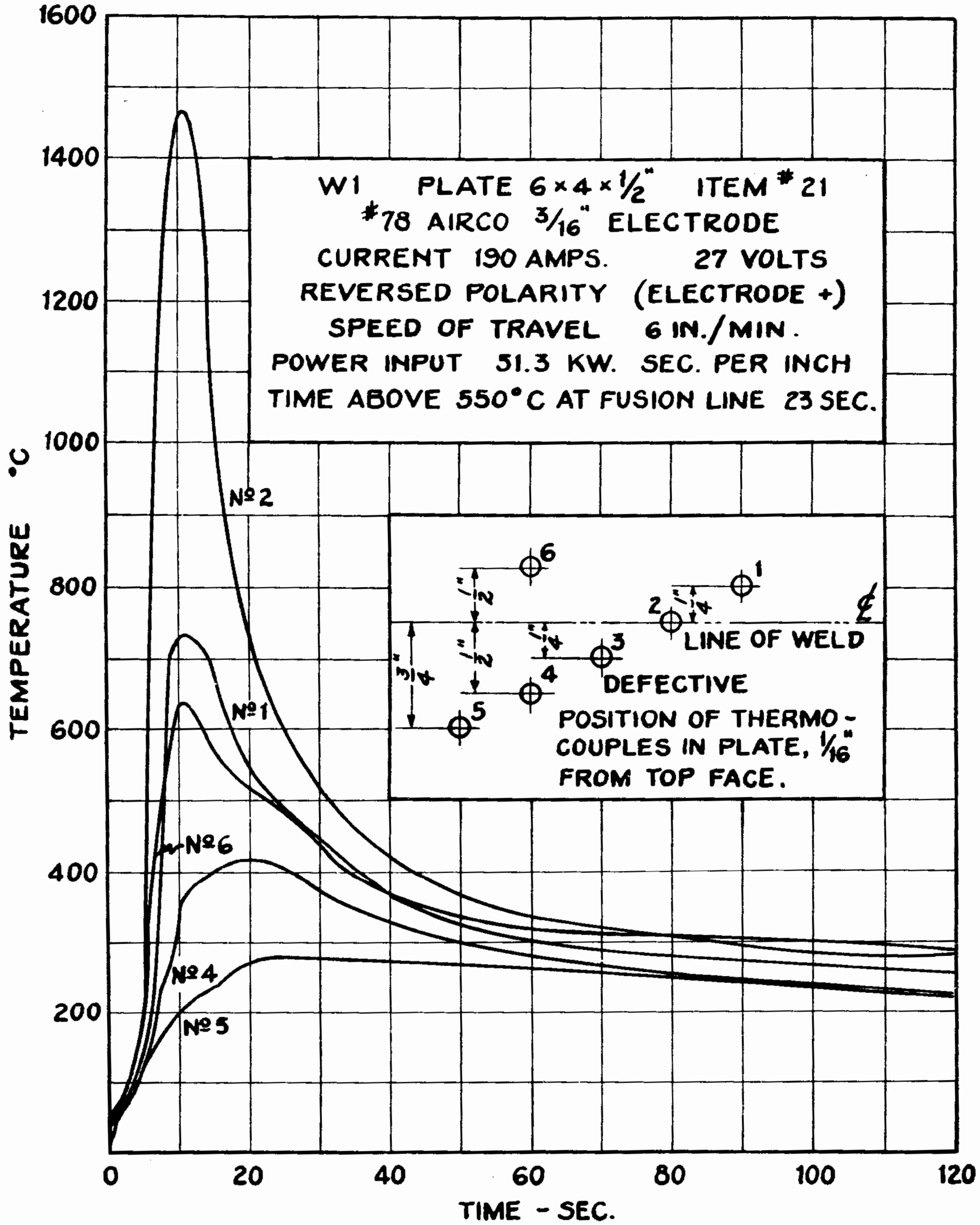
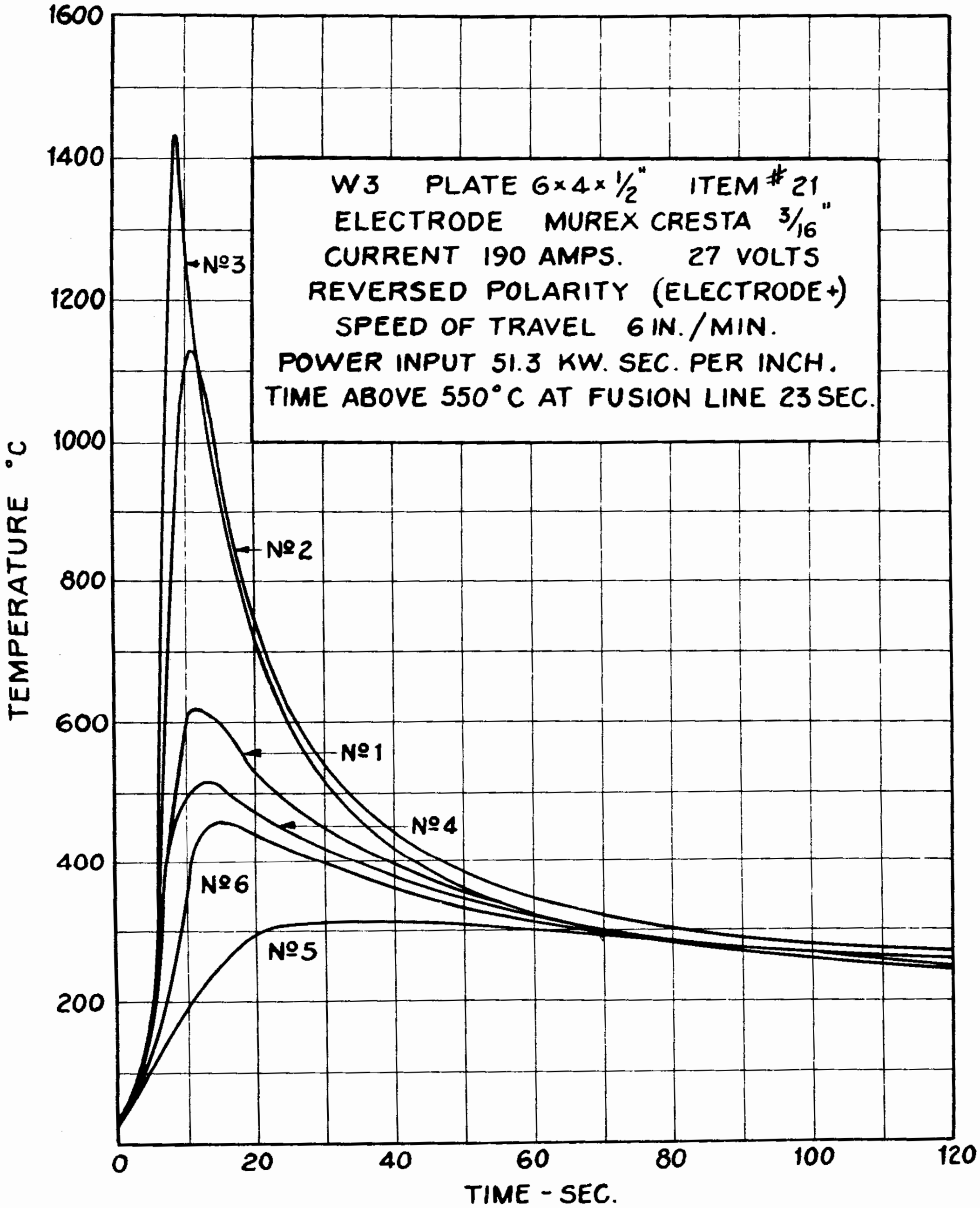

W9 PLATE 6 × 7 × 1/2" ITEM # 15
#78 AIRCO 3/16" ELECTRODE
CURRENT 175 AMPS. 25 VOLTS
REVERSED POLARITY (ELECTRODE +)
SPEED OF TRAVEL 6 IN./MIN.
POWER INPUT 43.75 KW. SEC. PER INCH
TIME ABOVE 550°C AT FUSION LINE 17 SEC.
№ 3
№ 1
№ 4
№ 5
TEMPERATURE °C
1600
1400
1200
1000
800
600
400
200
0
20
40
60
80
100
120
TIME - SEC.

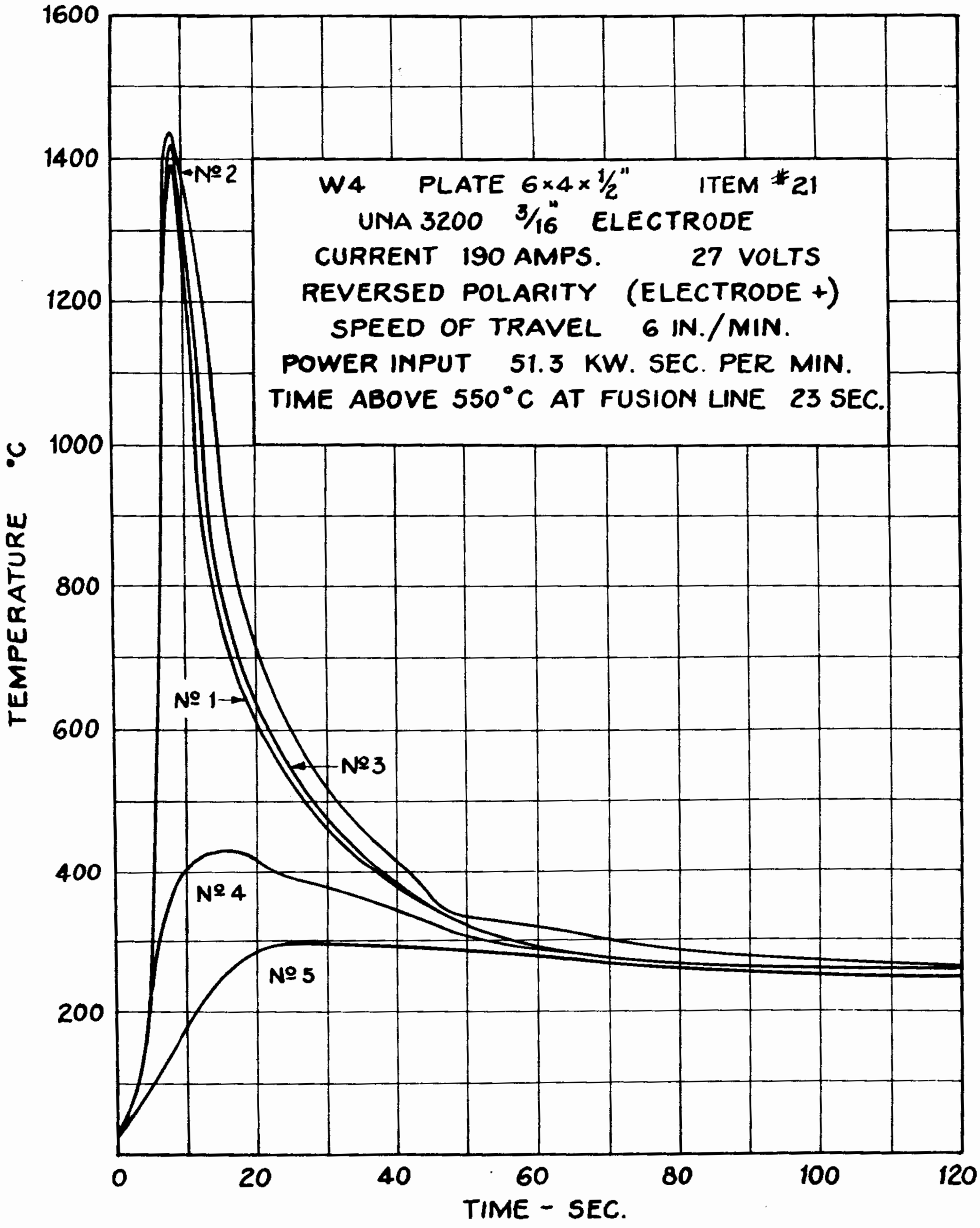
PLATE 8


W1 PLATE 6 × 4 × 1/2" ITEM # 21
#78 AIRCO 3/16" ELECTRODE
CURRENT 190 AMPS. 27 VOLTS
REVERSED POLARITY (ELECTRODE +)
SPEED OF TRAVEL 6 IN./MIN.
POWER INPUT 51.3 KW. SEC. PER INCH
TIME ABOVE 550°C AT FUSION LINE 23 SEC.
Nº 2
Nº 1
Nº 6
Nº 4
Nº 5
LINE OF WELD
DEFECTIVE
POSITION OF THERMO-COUPLES IN PLATE, 1/16" FROM TOP FACE.
TEMPERATURE °C
TIME - SEC.
0
20
40
60
80
100
120
200
400
600
800
1000
1200
1400
1600



W3 PLATE 6×4×½" ITEM # 21
ELECTRODE MUREX CRESTA 3/16"
CURRENT 190 AMPS. 27 VOLTS
REVERSED POLARITY (ELECTRODE+)
SPEED OF TRAVEL 6 IN./MIN.
POWER INPUT 51.3 KW. SEC. PER INCH.
TIME ABOVE 550°C AT FUSION LINE 23 SEC.
Nº3
Nº2
Nº1
Nº4
Nº6
Nº5
1600
1400
1200
1000
800
600
400
200
TEMPERATURE °C
0
20
40
60
80
100
120
TIME - SEC.

PLATE 10



W4 PLATE 6×4×½" ITEM #21
UNA 3200 3/16" ELECTRODE
CURRENT 190 AMPS. 27 VOLTS
REVERSED POLARITY (ELECTRODE +)
SPEED OF TRAVEL 6 IN./MIN.
POWER INPUT 51.3 KW. SEC. PER MIN.
TIME ABOVE 550°C AT FUSION LINE 23 SEC.
№ 1
№ 2
№ 3
№ 4
№ 5
TEMPERATURE °C
TIME - SEC.
1600
1400
1200
1000
800
600
400
200
0
20
40
60
80
100
120

PLATE 11

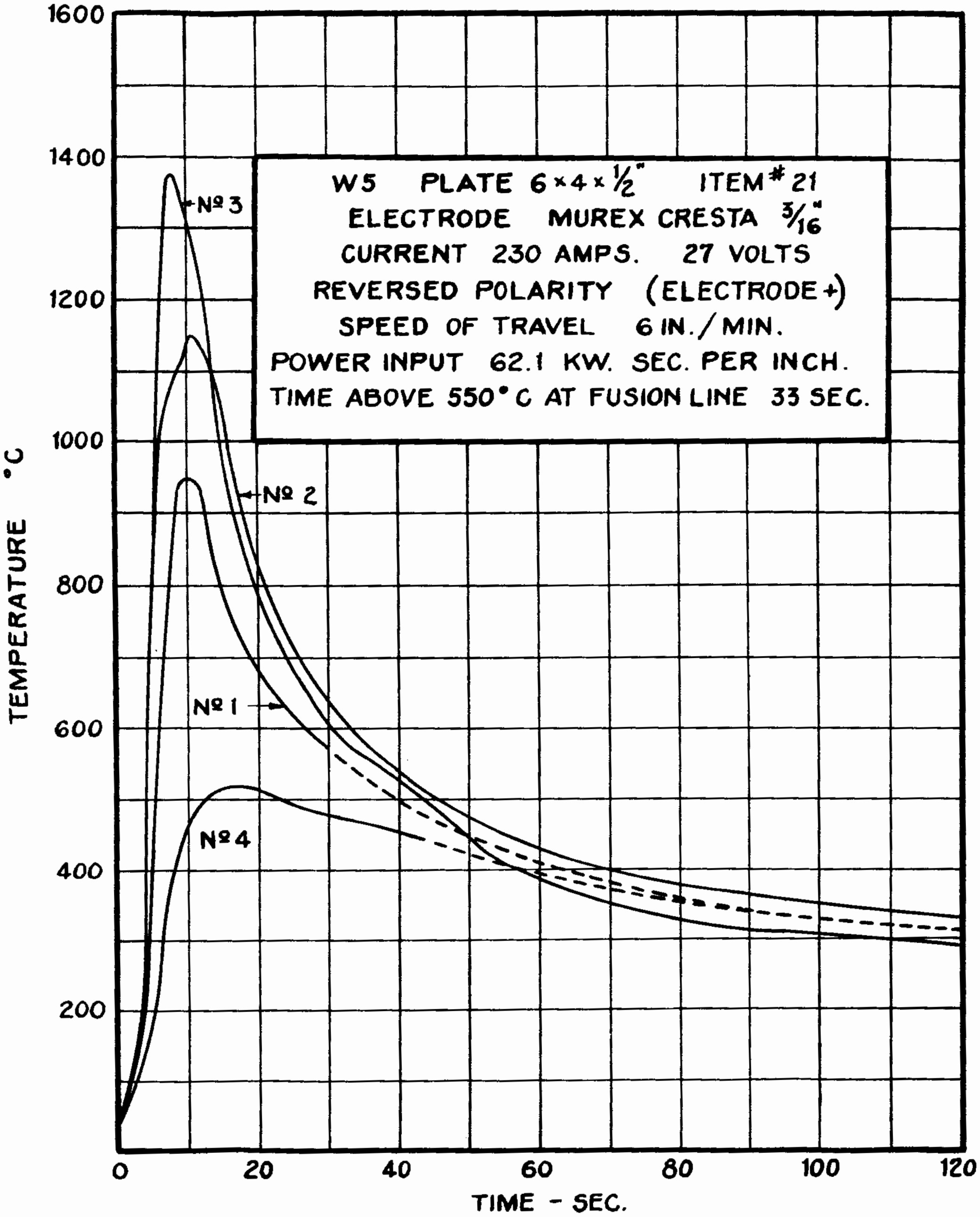
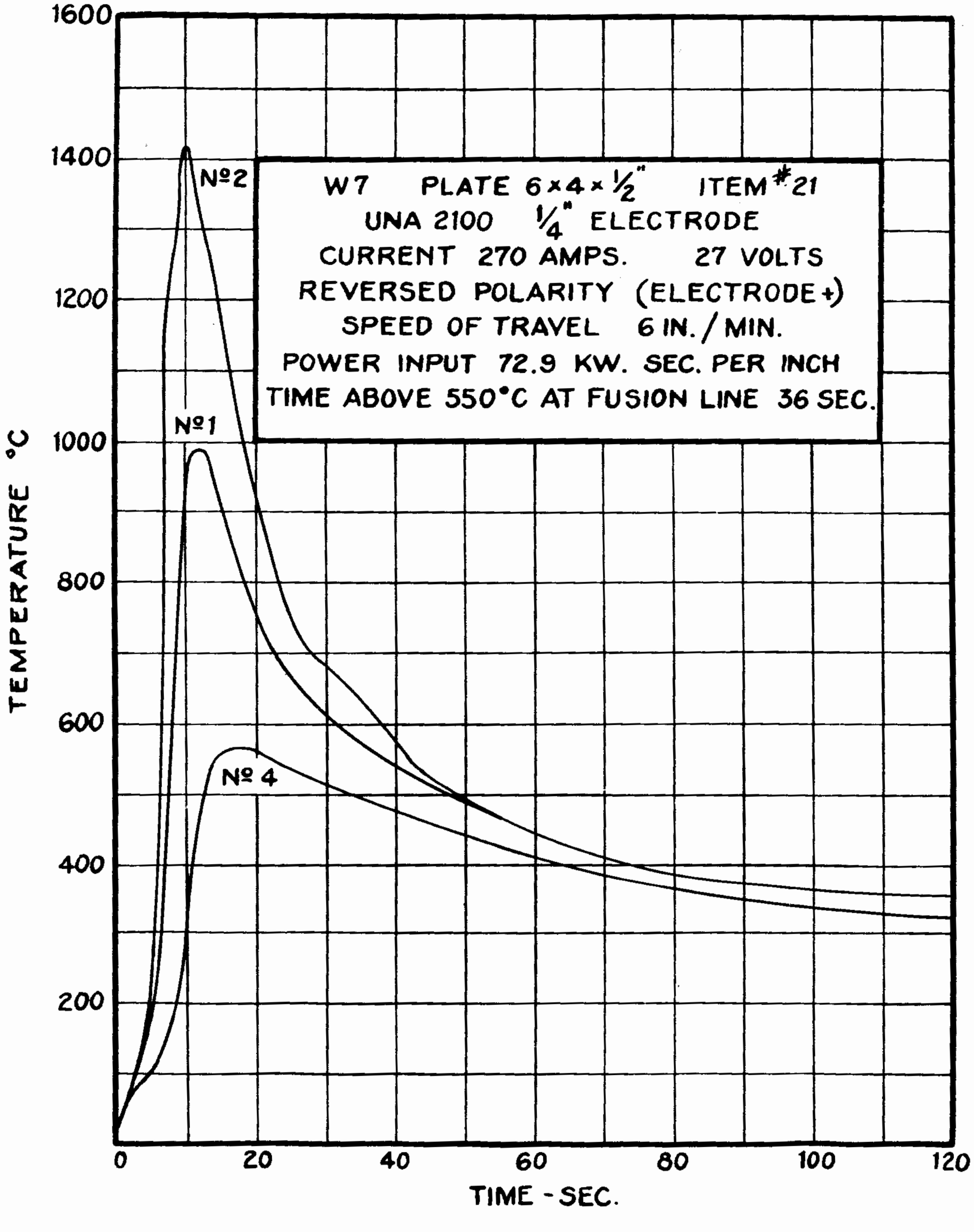
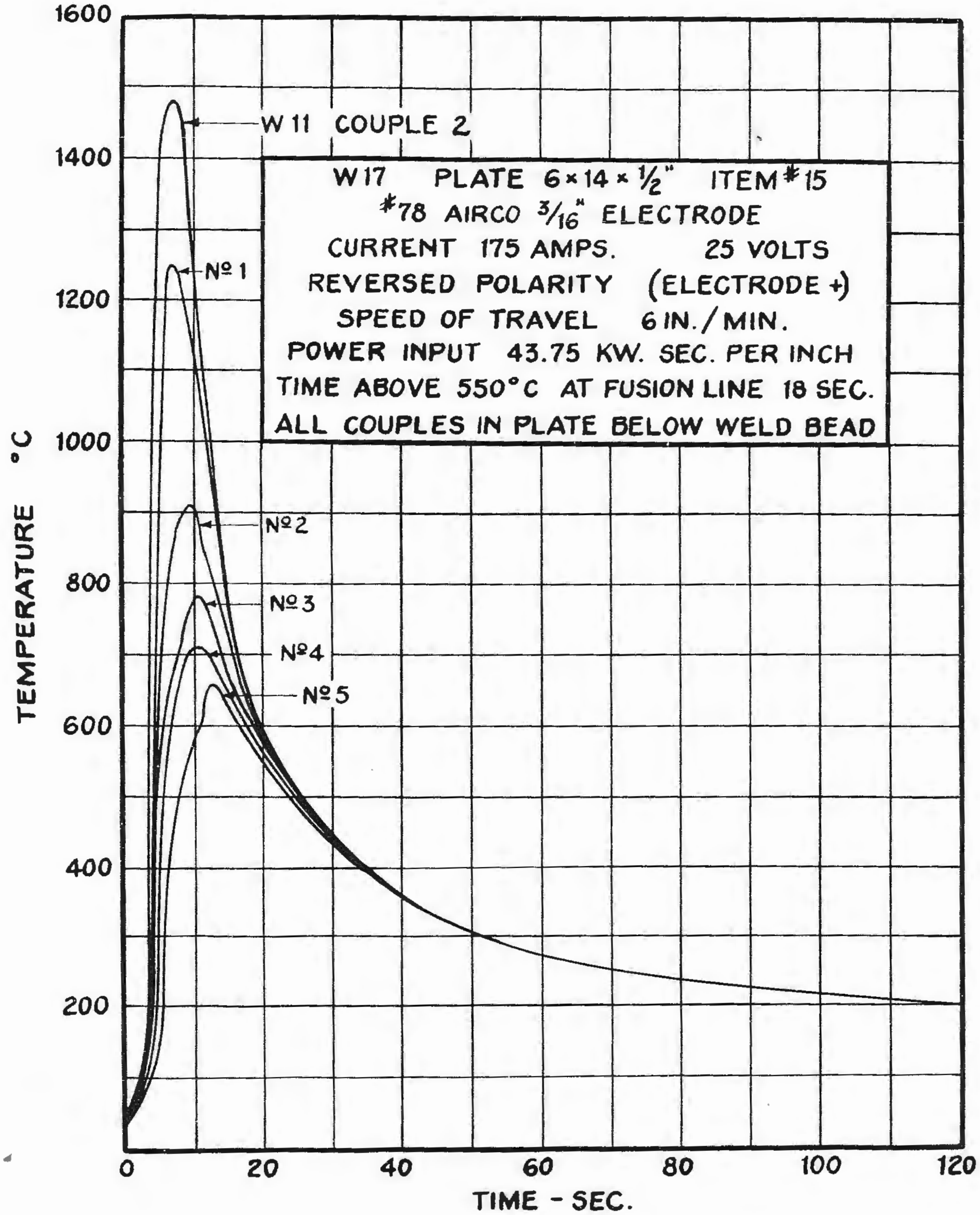

W5 PLATE 6 × 4 × 1/2" ITEM # 21
ELECTRODE MUREX CRESTA 3/16"
CURRENT 230 AMPS. 27 VOLTS
REVERSED POLARITY (ELECTRODE +)
SPEED OF TRAVEL 6 IN./MIN.
POWER INPUT 62.1 KW. SEC. PER INCH.
TIME ABOVE 550° C AT FUSION LINE 33 SEC.
Nº 3
Nº 2
Nº 1
Nº 4
TEMPERATURE °C
1600
1400
1200
1000
800
600
400
200
0
20
40
60
80
100
120
TIME - SEC.

PLATE 12


W7 PLATE 6×4×½" ITEM #21
UNA 2100 ¼" ELECTRODE
CURRENT 270 AMPS. 27 VOLTS
REVERSED POLARITY (ELECTRODE +)
SPEED OF TRAVEL 6 IN./MIN.
POWER INPUT 72.9 KW. SEC. PER INCH
TIME ABOVE 550°C AT FUSION LINE 36 SEC.
Nº2
Nº1
Nº4
1600
1400
1200
1000
800
600
400
200
TEMPERATURE °C
0
20
40
60
80
100
120
TIME - SEC.



1600
1400
1200
1000
800
600
400
200
TEMPERATURE °C
0
20
40
60
80
100
120
TIME - SEC.
W 11 COUPLE 2
Nº 1
Nº 2
Nº 3
Nº 4
Nº 5
W 17 PLATE 6 × 14 × 1/2" ITEM # 15
78 AIRCO 3/16" ELECTRODE
CURRENT 175 AMPS. 25 VOLTS
REVERSED POLARITY (ELECTRODE +)
SPEED OF TRAVEL 6 IN./MIN.
POWER INPUT 43.75 KW. SEC. PER INCH
TIME ABOVE 550°C AT FUSION LINE 18 SEC.
ALL COUPLES IN PLATE BELOW WELD BEAD

PLATE 14

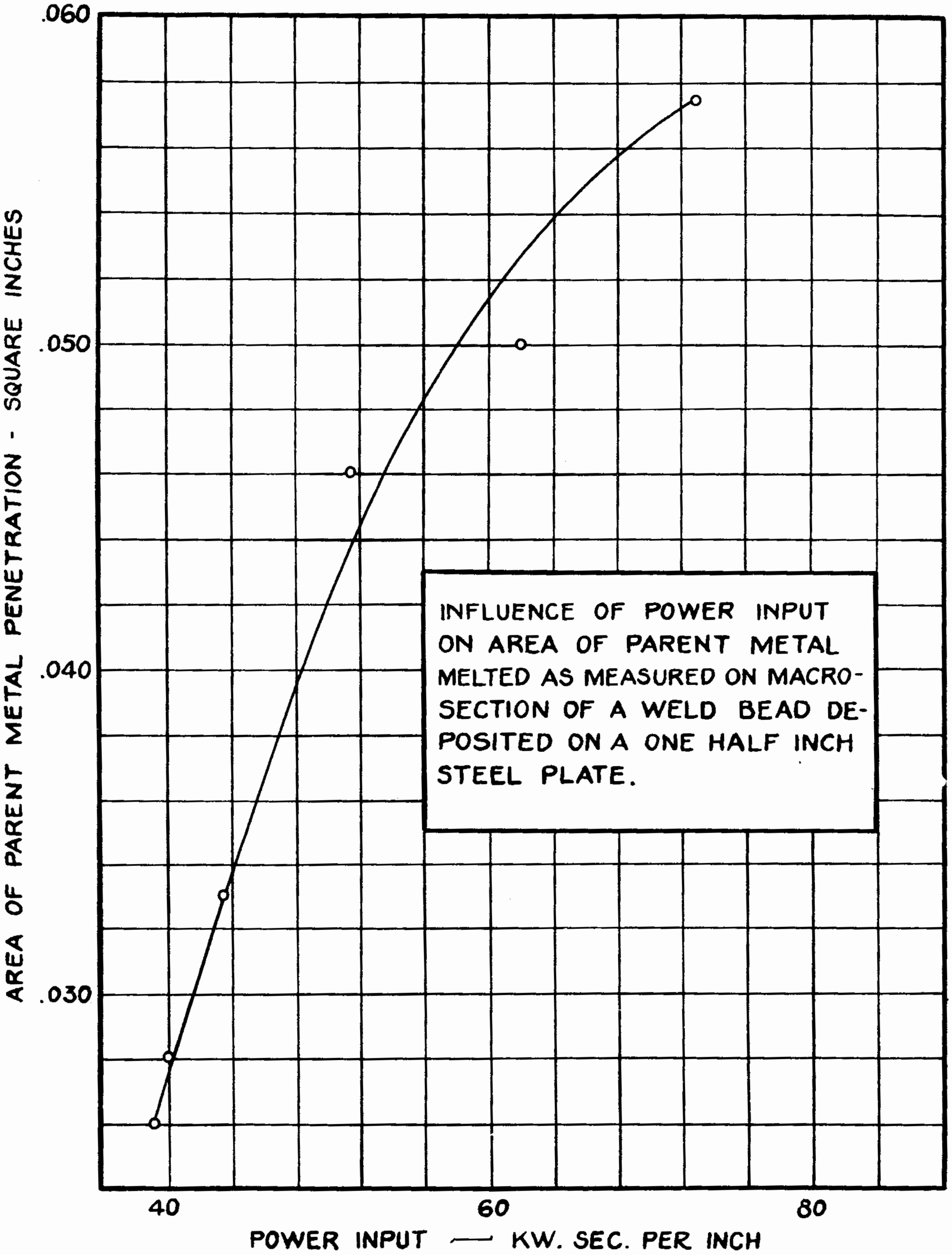
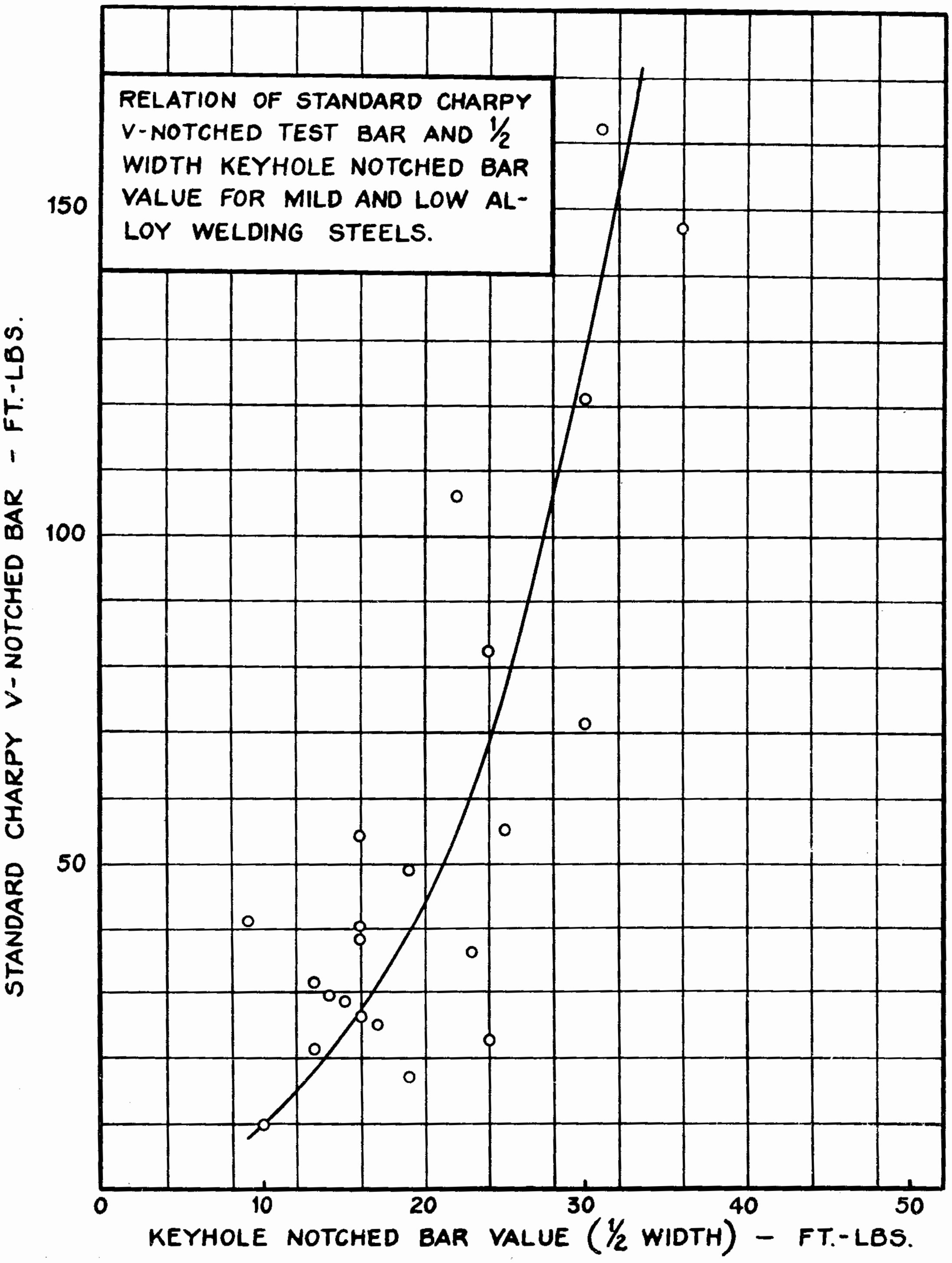

.060
.050
.040
.030
AREA OF PARENT METAL PENETRATION - SQUARE INCHES
40
60
80
POWER INPUT — KW. SEC. PER INCH
INFLUENCE OF POWER INPUT ON AREA OF PARENT METAL MELTED AS MEASURED ON MACRO-SECTION OF A WELD BEAD DE-POSITED ON A ONE HALF INCH STEEL PLATE.

PLATE 15

4 ×

100 ×

MACRO AND MICRO-PHOTOGRAPH SHOWING CRACK FORMATION ADJACENT TO A BEAD WELD.



RELATION OF STANDARD CHARPY V-NOTCHED TEST BAR AND 1/2 WIDTH KEYHOLE NOTCHED BAR VALUE FOR MILD AND LOW ALLOY WELDING STEELS.
STANDARD CHARPY V-NOTCHED BAR - FT.-LBS.
150
100
50
0
10
20
30
40
50
KEYHOLE NOTCHED BAR VALUE (1/2 WIDTH) - FT.-LBS.

PLATE 17